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High-power FFAG-based heavy-ion and proton drivers

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DISCLAIMER

HIGH-POWER FFAG-BASED HEAVY-ION AND PROTON DRIVERS*

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Abstract

Fixed-Field Alternating-Gradient (FFAG) accelerators are being proposed as an alternative to Super-Conducting Linacs (SCL), Rapid-Cycling Synchrotrons (RCS) and Cyclotrons for the acceleration of very intense Heavy-Ion and Proton beams in the medium energy range. One application is the acceleration of ions of Uranium-238 to an energy of 400 MeV/u, and the average power of 400 kWatt, and the other a 1-GeV Proton Driver with an average beam power of 10 MWatt. One or two FFAG rings are needed for acceleration of both beams. They adopt a Non-Scaling Lattice (NSL) to reduce the size and the cost of the accelerator. The continuous wave (CW) mode of operation is achieved with the method of Harmonic Number Jump (HNJ).

INTRODUCTION

High-Power Proton and Heavy-Ion Drivers have been proposed for a variety of applications: Spallation Neutron Sources; Tritium Production; Nuclear Waste Transmutation; Energy Production by impinging a proton beam on a sub-critical fissionable nuclear core; production of Radio-Isotopes and Exotic Nuclear Fragments; high-intensity secondary beams such as Kaons and Muons for Nuclear and High-Energy Physics; and more. The proton beam energy and that of heavy ions ranges from 1 to about 10 GeV. The required average beam intensity though is more demanding, ranging from at least 1 to possibly 10 MWatt, and above. Different modes of operation are also considered: low repetition rate of a few tens of pulses per second (Hz); high repetition rate of a few thousand pulses per second (kHz); and continuous mode of operation (CW).

There are several types of Particle Accelerator that can be used for the acceleration of intense hadron beams. These are RCS, SCL, Cyclotrons, and FFAG accelerators. Cyclotrons are similar to FFAG accelerators, but have also some major differences and limitations. SCL's represent the ideal configuration for a high-power Proton or Heavy-Ion Driver, and are the most straightforward solution to adopt. However, they require considerable cryogenic and RF systems, and are expensive. RCS's on the other hand are expected to be more economical but are limited in repetition rate. FFAG accelerators are expected to perform in between SCL's and RCS's. Whereas the beam is accelerated in one single pass in the SCL, and circulates for several thousand revolutions in the RCS, the beam is accelerated in the FFAG accelerator over a few tens or at most a few hundreds of revolutions.

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FFAG MAIN FEATURES

The most important feature of the FFAG accelerator is that the guiding magnetic field is kept constant with time. Thus the acceleration rate is not limited by the magnetic field but by the accelerating RF system itself. Because of the higher repetition rate, higher beam power can be achieved with lower beam intensity.

At the same time, because the magnetic field is kept constant, and has a limited range across the radial aperture, the momentum excursion between injection and extraction is reduced. Depending on the ring lattice choice, the momentum range accepted in the acceleration cycle is at most $\Delta p/p = \pm 30$ to $\pm 50\%$. Thus depending on the application and the required energy range, the accelerator complex can be made of a single or two or even three FFAG rings of the same circumference and structure concentric to each other, to ease the transfer, and all located in the same enclosure. This is the case of the three FFAG rings in the KURRI facility [1] for the final energy of 150 MeV. Figure 1 is a proposed Proton Driver for a Neutrino Factory also comprising 3 FFAG rings [2].

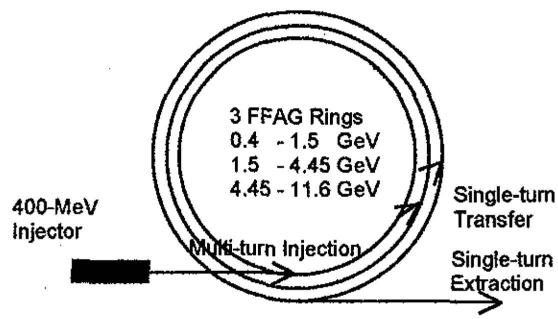

Figure 1: Schematic layout of a proposed FFAG for a Neutrino Factory [2].

PROPOSED FFAG PROJECTS

Table 1 gives the summary of three proposed proton FFAG accelerators. The first (A) is the 1.5 GeV FFAG proposed as a new injector [3] to the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL); the second (B) is a low energy accelerator, operating at very high repetition rate and also in CW mode, for energy production [4]; and the last (C) is a similar FFAG complex for the acceleration of ions of Uranium 238 for Rare-Isotopes production [5]. Project A was studied and proposed as the new injector to the AGS replacing the 1.5 GeV Booster for the upgrade program to an average beam power of 1 MW at 28 GeV. Its design has been taken as the reference for all other similar projects that were derived with convenient scaling rules [6]. Table 1 does not include two other FFAG projects proposed as 12-GeV Proton Drivers for the Neutrino Factory and Muon Collider [2, 7]. Projects B and C have identical FFAG ring layouts with the same lattice and magnet configurations. They are both for relatively lower beam energy and represent examples of how the same FFAG accelerator complex can be used for acceleration of protons and of heavy ions (Uranium 238).

Table 1: Examples of proposed FFAG-based Proton and Heavy Ion Drivers

Project	A (proton)	B (proton)	C (H.I.)
Energy, GeV/u	0.4 – 1.5	0.05 – 1.0	0.015 - 0.40
Rep. Rate	2.5 - 5.0 Hz	1 kHz - CW	1 kHz - CW
Ave. Pow., MW	0.050	10	0.4
Ave. Curr., mA	0.033	10	0.0042 - ion
No. of Rings	1	2	2
Circumfer., m	807	204	204

FFAG MAGNET CONFIGURATIONS

There are several types of FFAG configuration, but mostly they fall into two categories: *Spiral* and *Radial* FFAG's, and sometime a combination of both [8]. In the *Radial* configuration, magnets are typically sector-shaped with a radial field profile in the body of the magnet itself. In the latter case there are two possible choices of magnet configuration: the *Scaling Lattice* (SL) and the *Non-Scaling Lattice* (NSL) [9]. The SL has a hyperbolic field profile with a field index set such that the chromaticity, that is the variation of the lattice functions with beam momentum, is fully compensated. The NSL does not compensate for the chromaticity since the field profile is linear with a constant gradient in each magnet. As a consequence, there is a large variation of betatron tunes with the beam momentum. All the examples of Table 1 are of the NSL type. They make use of FDF Triplets that have been proven to be very effective in strong focusing systems, with very low amplitude and dispersion functions [10].

NON-SCALING FFAG ACCELERATORS

The lattice of a NLS FFAG with LFP is a sequence of FDF Triplets. The beam is injected on an orbit placed on the inside of the ring, spirals during acceleration toward the outside, and is extracted from an outer orbit. There are two major drifts: a long one, *s*, and a minor one, *g*, separating the magnets.

As one can notice from Table 1 there are two distinct circumferences: a major one of 807 m that corresponds to the reference design based on the AGS circumference, and a minor one of 204 m for the lower energy cases. Table 2 gives a list of the main magnet lattice parameters for the two circumference cases. The optimum design, that ensures beam stability over the required momentum range and reasonable magnet size and drift lengths, requires a periodicity as large as possible, and a large circumference to reduce the betatron tune splitting caused by the curvature effect. Two main parameters are the length *s* of the long drift that should be long enough to accommodate RF cavities, collimators, and injection and extraction components, and the radial width *w* required for the momentum excursion during acceleration. The width *w* is to be small enough to match the radial extension of the RF cavities especially in the case of very high frequency.

Figure 2 gives the plot of the lattice functions along the length of one period for the low-energy proton FFAG project B of Table 1. The lattice functions vary with energy, as it is shown by the variation of the betatron tunes during acceleration in Figure 3. Closed orbits are plotted in Figure 4 at different momenta $\delta = (p - p_{inj}) / p_{inj}$ in the acceleration cycle along the length of one period.

Table 2: Structure of the FFAG Rings

Projects	A	B & C
No. of Periods	136	80
Period Length, m	5.93	2.55
Long Drift s, m	2,534	1.089
Short Drift g, m	0.30	0.129
F-Sector Arc Length, m	0.70	0.301
D-Sector Arc Length, m	1.40	0.602
Radial Width w, cm	17.3	11.2

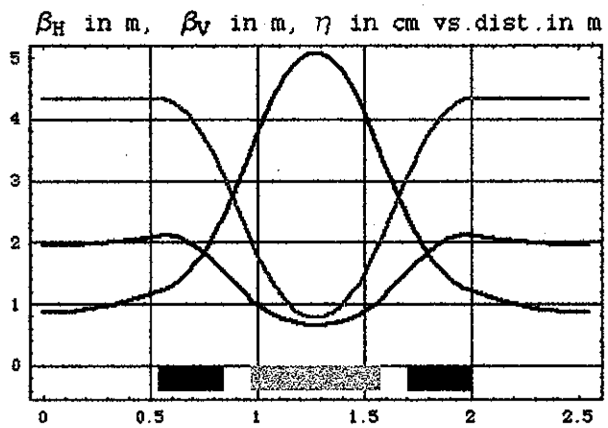

Figure 2: Lattice Functions along the length of a period.

ACCELERATION METHODS

In the case of acceleration of low-energy protons and ions of Uranium, the beam velocity varies considerably during the cycle. A frequency-modulated RF cavity system, like those using ferrite, will not do the job well, except for cases with low repetition rates. An alternative is to use broad-band, constant frequency RF cavities, such as those used in the J-Parc accelerator complex [11]. In this case the RF frequency is relatively low (a few MHz), and the voltage is only a few tens of kVolt per cavity. Another approach that would allow a considerably higher repetition rate is the method of Harmonic Number Jump (HNJ) [12]. Eventually, the HNJ method could also be used for a continuous beam mode of operation, since on a given orbit the beam is accelerated by a pre-programmed RF voltage, the profile being kept constant across the width of the cavity at all times, and all orbits can simultaneously be occupied by beam.

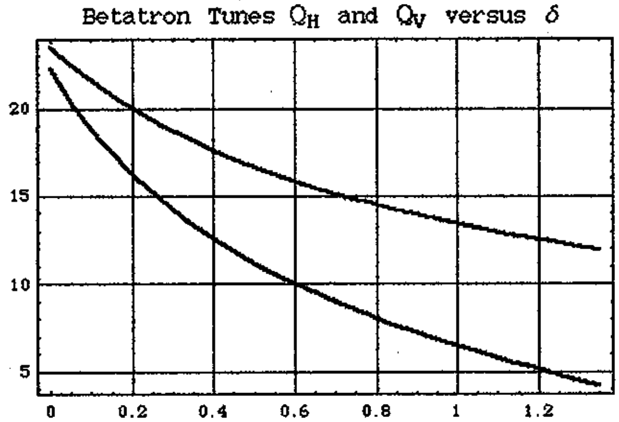

Figure 3: Betatron Tunes during the Acceleration Cycle.

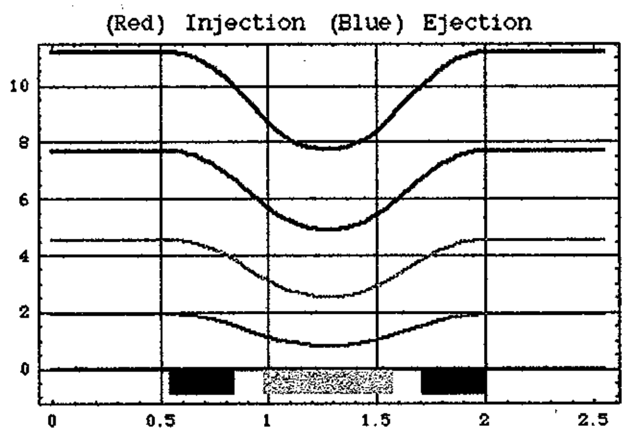

Figure 4: Closed Orbits during the Acceleration Cycle.

Acceleration by Harmonic Number Jump

A higher repetition rate not only is desirable to boost the beam power and to avoid problems with space charge and with multiple resonance crossing in the NSL FFAG, but also to ease the performance requirements of the ion source and of multi-turn injection into the first FFAG ring. The HNJ method allows the use of superconducting RF cavities at very high constant frequency, in the range of several hundred MHz or even in the GHz range. Acceleration requires a programmed energy gain that varies between cavity crossings, to allow for the change of the transit time between cavities that corresponds to a *jump* of one or more RF harmonics. If f_{RF} is the RF frequency, obviously the relation $f_{RF} = h\ \beta c/C$ holds where h is the (local, that is between two consecutive cavity crossings) harmonic number, C the distance between cavities, and βc the beam velocity. In a synchrotron, the harmonic number h is kept constant; as the beam velocity βc varies, then the RF frequency f_{RF} is adjusted accordingly. The HNJ method, on the other hand, requires that f_{RF} is kept constant so that as the beam velocity βc changes the harmonic number h will have to vary accordingly. This can be achieved only with a proper program of energy gain between cavity crossings [13]. It should be pointed out that, since the harmonic number h reduces during acceleration, the number of beam bunches at injection into the first ring cannot be larger than then harmonic number at extraction from the second ring.

CW Mode of Operation

By extrapolation, the HNJ method of acceleration can be used for the more convenient and useful Continuous Wave (CW) mode of operation where the beam is continuously injected, accelerated and transferred to the Target [2, 5]. The continuous injection will require that ions occupy simultaneously all orbits as they move in a spiral way in and out from one ring to the next. This requires that the beam from the source, prior to injection into the first FFAG ring, is pre-chopped at the injection revolution frequency to allow for the gap corresponding to the ratio β_1/β_2 of the beam velocity at injection to the velocity at extraction.

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